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Airborne radio echo sounding of outlet glaciers in Greenland

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Abstract. We used a coherent radar depth sounder operating at 150 MHz to collect ice thickness data on outlet glaciers in northwestern Greenland. The radar data were collected in conjunction with laser surface elevation measurements and were tagged with GPS information for accurate geolocation. The radar signals were corrupted by multiple echoes between the aircraft and the ice surface, as well as between the ice surface and the ice-bedrock interface. We applied the homomorphic deconvolution technique to remove multiple echoes successfully and have identified the grounding line of a long ice shelf in northwestern Greenland.

1. Introduction

The Greenland ice sheet contains about 7 per cent of the world's fresh water and is the largest ice mass in the northern hemisphere. It is expected that climate perturbations may have an immediate effect on the mass balance of the Greenland ice sheet through melting and run-off as well as precipitation.

To determine whether the Greenland ice sheet mass is increasing or decreasing and how this will affect the global sea level, NASA began a coordinated programme of measurements of the Greenland ice sheet in 1991 (Krabill *et al.* 1995a). The long-term objective of this programme is to determine the ice thickening or thinning rates through repeated airborne laser altimeter surveys (Krabill *et al.* 1995b). The secondary objective is to obtain ice thickness information for the study of ice dynamics.

Although many radar echo soundings have been made of the interior ice sheet, very few measurements have been made of the outlet glaciers because of the difficulty in sounding these glaciers with earlier radio echo sounding systems. Basal topography and ice thickness are essential in the study of the dynamics of outlet glaciers.

A NASA P-3 aircraft, equipped with Global Positioning System (GPS) controlled navigation, a laser altimeter, and a radar depth sounder, was used to collect surface topography and ice thickness data. The laser altimeter is accurate to about 10 cm (Krabill *et al.* 1995b). The radar depth sounder described here is capable of measuring polar ice sheet thickness to about 4000 m and lesser ice thickness in temperate glaciers.

During the 1995 field season, we collected radar echo sounding data of the Petermann and several other outlet glaciers. These data showed that the Petermann glacier terminates in a long, floating ice shelf tens of kilometres long.

In this letter we provide a brief system description and experimental results along with geophysical interpretation of the Petermann radar data. We also discuss the theory and present results of the homomorphic deconvolution procedure.

2. System description

The radar depth sounder we used in this study is a modified and improved version of the Coherent Antarctic Radar Depth Sounder (CARDS) (Raju *et al.* 1990). Our airborne, coherent radar system operates at a centre frequency of 150 MHz. Operating at a pulse repetition frequency (PRF) of 9800 Hz, the transmitter generates a pulse that is frequency modulated (chirped) over a bandwidth of 17 MHz with a duration of 1·6 μs and a peak power of 200 W. The receiver, protected during transmit events by a blanking switch, compresses the received signal in a weighted SAW compressor resulting in a compressed pulse width of 60 ns and a depth resolution of about 5 m in ice (refractive index, $n=1{\cdot}78$). The received signal is downconverted to baseband via coherent detection providing in-phase and quadrature (I and Q) analog outputs that are digitized in pairs with two 8-bit A/D converters at a rate of 18·75 megasamples s^{-1} (MSPS). Coherent integration is then performed by summing complex data vectors from 256 consecutive transmit-receive periods. The data are detected by computing the power in each record (I^2+Q^2) and then integrated further (incoherent integration) by summing four consecutive detected signals. Finally, the data are displayed to the user and are also recorded (along with position and time data provided by the on-board GPS receiver) at a rate of about 9 kbytes s^{-1} on a removable hard disk.

Separate transmit and receive antenna arrays were mounted beneath the left- and right-wings, with each array composed of four, half-dipole antennas. As the wings were tilted 6° above the horizontal, the theoretical two-way, half-power beamwidth of this antenna configuration was about 18° in the plane normal to the flight path and about 66° in the plane parallel to the flight path. The coherent integration serves as a low-pass filter on the data and is equivalent to reducing the along-track antenna beamwidth from about 66° to 7° at the nominal velocity.

We believe the pulse compression, coherent processing and the bistatic antenna arrangement are the features that permitted this system to succeed in sounding these glaciers.

3. Experiment description and data processing

In May 1995, an overflight of the Petermann glacier was flown principally along a flow line. This flight line was continuous, extending from the interior of the inland ice sheet to the ocean. During data acquisition, the aircraft altitude was approximately 500 m above local terrain and the air speed was about 130 m s^{-1}. Figure 1 shows the flight line along with an echogram of the Petermann glacier.

Figure 1 (top) shows the radio echogram from the Petermann glacier prior to homomorphic deconvolution. In the left portion of this echogram, the return from the surface and the bottom are clearly identifiable. Also seen is a multiple echo resulting from a multipath between the ice surface and the aircraft. The distance between the true return from the ice surface and its multiple echo is approximately 60 pixels, and, while each pixel corresponds to 4·49 m in ice, in air each pixel corresponds to 8 m so that the separation between the true and multiple echoes is about 480 m, which corresponds to the nominal aircraft altitude of 500 m. In the right half of this echogram we see numerous multiple echoes again arising from the

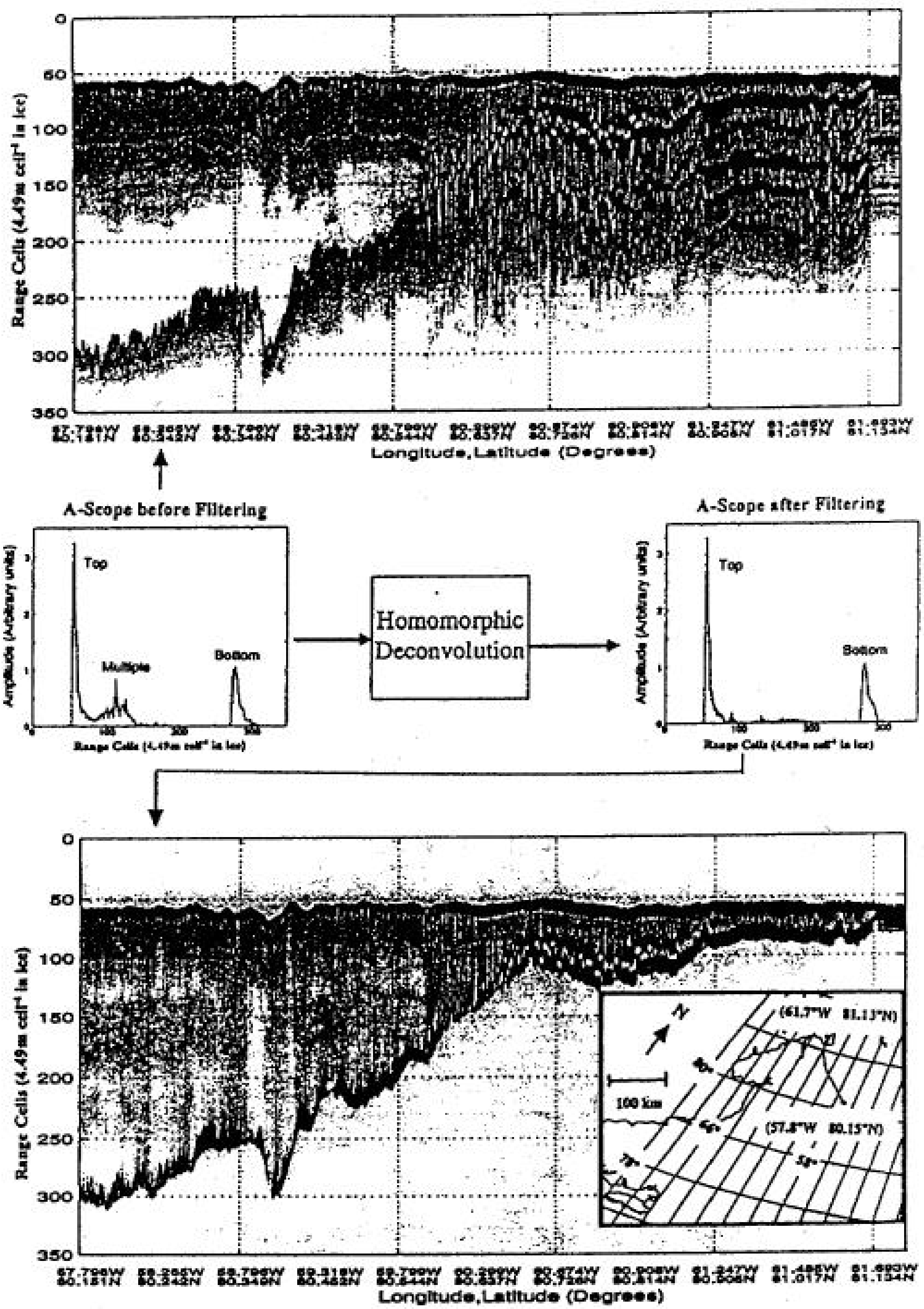

Figure 1. Radio echogram of the Petermann glacier before (above) and after homomorphic deconvolution (below). Flight lines are shown on a map of the Petermann glacier (inset). Radar echo intensity as a function of transit time or depth are shown in traditional A-Scope format before and after homomorphic deconvolution (centre).

ice surface-aircraft multipath, as well as multiple echoes due to multipath between the ice surface and the ice-water interface.

To remove these artefacts without removing other real features in the data, we applied homomorphic deconvolution, to data between the locations 57·8° W and 80·15° N and 60° W and 80·6° N. From this point to the calving front, the data consisted of a variety of multipath echoes yet the bottom echo was discernible, therefore the clutter beyond the bottom echo was masked out.

In homomorphic deconvolution a signal composed of the convolution of two signals is converted to a signal space where the two signals are now summed. In our case, we have a record of data that can be represented by the convolution of our pulse (and its delayed image) with a series of impulses corresponding with the reflection characteristics of the ice and bedrock. Oppenheim and Schafer (1968) developed much of the theory behind homomorphic deconvolution. Essentially, by transforming our data first to the frequency domain (transforming convolutional processes into multiplicative ones) and then taking the complex logarithm of this frequency domain data (transforming multiplicative processes into additive ones), we are able to subtract the multiple reflection components without adversely affecting the remainder of the data. Returning to the original time domain of our data requires an undoing of the sequence just described (i.e., performing a complex exponential and then transformation from the frequency domain to the time domain via Fourier transform).

To separate the multiple reflections from the desired data successfully, the time-domain data must be either a minimal-phase or a maximal-phase sequence; however our data were neither—they were a mixed-phase sequence. Therefore we converted them into a minimal-phase sequence by multiplying our data sequence by an exponential weighting prior to applying the deconvolution process (Schafer 1969). Removal of this exponential weighting was then required following the completion of the deconvolution.

In the middle of figure 1 is a display of the intensity of the radar echo signal as a function of transit time or depth in the traditional A-Scope format taken from the radio echogram above (position denoted by arrow). The display on the left is from the echogram prior to the homomorphic deconvolution while the display on the right shows the same signal after this process. Clearly, the multiple echo from the surface is removed while the actual signals remain.

4. Results

In the lower part of figure 1 we see the result of the homomorphic deconvolution. The multiple echo from the surface in the left half (above) is removed and the numerous echoes in the right half are also removed, making the determination of the ice thickness possible by finding the distance between the surface return and the bottom return. A rapidly decreasing thickness is seen as the ocean is approached, except for the valley at around 80·40° N/58·60° W. We believe the grounding line (where the glacier begins to float) may lie between points 80·59° N/59·88° W and 80·65° N/60·39° W as it appears that the glacier begins to experience bottom crevassing. The glacier thins rapidly immediately beyond the grounding line but then this ice shelf reaches a relatively constant thickness finally reaching a thickness of 60 m at the calving front. We also associate the location of the grounding line with the sharp increase in basal reflection strength also observed in this region.

5. Conclusions

We have developed a coherent depth sounder that is capable of measuring the thickness of outlet glaciers. Multiple echoes arise from the ice surface-airplane multipath. By applying homomorphic deconvolution we were able to remove these multiple returns, enabling us to measure the thickness of the Petermann glacier from the Greenland ice sheet continuously to its calving front at the ocean. We also detected evidence of the grounding line.

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